Transverse surface acoustic wave detection by scanning acoustic force microscopy

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We present a scanning acoustic force microscope (SAFM) for the study of surface acoustic wave (SAW) phenomena on the submicron lateral scale. Until now, SAWs with in-plane oscillation components could only be studied effectively via nonvanishing out-of-plane oscillation contributions. By operating the microscope in lateral force mode, where both bending and torsion of the cantilever are detected, additional amplitude-dependent signals are found, which are due to the interaction with purely in-plane polarized surface oscillations. To demonstrate the capabilities of this type of SAFM, Love waves were studied on the surface of layers deposited on ST-cut quartz with SAW propagation perpendicular to the crystal *X*-axis. The phase velocity of the wave as well as the amplitude of a standing wave field was measured and compared to calculated values. [S0003-6951(98)03233-1]

Surface guided acoustic waves are of great interest for many kinds of electronic frequency and time domain filtering purposes, as well as for chemical sensing applications. Recently, in-plane polarized leaky modes have attracted much attention since they offer higher phase velocities, and thus, higher operation frequencies with the same device structure sizes. Especially, the surface transverse wave (STW),[1] i.e., a transversely polarized pseudo surface acoustic wave, and the quasilongitudinally polarized high velocity pseudo surface acoustic wave[2] (HVPSAW) modes are very promising for device applications. For example, on ST-cut quartz the velocity of the STW perpendicular to the crystal *X*-axis is about 60% higher than the Rayleigh mode parallel to the *X*-axis. The HVPSAW can almost reach the velocity of the longitudinal bulk wave. Additionally, the in-plane polarization of these waves is advantageous for the investigation of the selective adsorption of chemical molecules in layers adjacent to a liquid environment. The vanishing vertical oscillation components prevent energy losses due to the excitation of compressive waves in the fluid. The coupling is thus solely due to frictional effects.

Despite the increasing importance of in-plane polarized surface guided acoustic modes, there is a lack of tools for their characterization. The most common and robust optical detection schemes for SAWs rely on the detection of nonvanishing displacement components normal to the surface of the material. An effective wave detection is possible if the surface of the solid is periodically deformed, thus providing a diffraction grating for an incident laser beam.[3] Also, the pure in-plane oscillation due to acoustic waves leads to a periodic change of the sample's properties. In particular, the refractive index changes due to the acoustic stress field leading to a change of the sample's specular and diffuse reflectivity. Using sophisticated techniques, like differential interferometry, where the speckle field that originates from two interfering beams coming from a single laser source is recorded, in-plane oscillation components can be detected.[4] However, the lateral resolution is limited by the optical spot size to some micrometers. These techniques are thus not useful for the mapping of wave fields at frequencies in the GHz range.

With the STM-based scanning acoustic tunneling microscope[5] the phase and the amplitude of SAWs of arbitrary polarization can be studied with atomic resolution,[6] but one is restricted to conducting samples, thus excluding typical SAW devices on piezoelectric substrates from the analysis.

The technique presented in this letter allows the detailed analysis of transverse acoustic wave propagation with submicron lateral resolution. It is based on the scanning acoustic force microscope (SAFM),[7] which shows no sensitivity to pure in-plane oscillations. In conventional SAFM, the additional contributions to the cantilever bending arising from the interaction between the oscillating surface and the SAFM tip is analyzed. The nonlinearity in the tip–surface interaction, namely, the nonlinear force-versus-distance curve, leads to the occurrence of detectable cantilever deflections, even though the surface oscillates at frequencies much higher than the resonance frequency of the cantilever. This mechanical-diode effect can be exploited to map acoustic amplitude distributions, as discussed below for standing wave fields. The introduction of two high frequency SAW fields at slightly detuned frequencies results in detectable deflection signals at harmonics of the difference frequency. The difference frequency can be chosen as low as some kHz. In the lateral force mode (LFM) the cantilever torsion due to in-plane oscillations is exploited in the same manner as described above. The setup of the LFM-SAFM is shown in Fig. 1. A similar nonlinear mechanism as for the detection of vertical oscillations allows the extraction of both the amplitude and phase information.

The system under investigation was a layered structure on ST-cut quartz with wave propagation direction perpendicular to the *X*-axis. Opposing interdigital transducers (IDTs) were used for the SAW excitation. On the bare sub-

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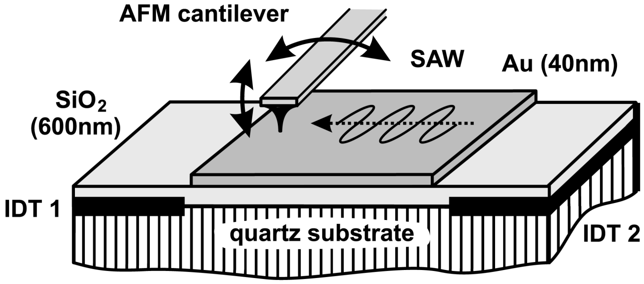

FIG. 1. Schematic of the experimental setup: Love waves are launched in the material system Au/SiO_2/ST quartz from the IDTs to the SAFM tip. The torsion and the bending of the cantilever is then analyzed.

strate a STW mode can be excited which converts into a Love-type SAW when a thin layer is attached to the substrate.[8] The oscillation is polarized purely in-plane and perpendicular to the propagation direction.

Most of the experiments were performed on a sample with a 600 nm SiO_2 layer covering the transducers and the propagation path. Within this path, a 40 nm thick gold layer was deposited in order to study the Love wave dispersion properties of the layered system. SAWs were excited at frequencies within the bandwidth of this delay line, which is about 1 MHz at a center frequency of 340 MHz (Fig. 2).

In order to study acoustic mixing, two Love waves with slightly detuned frequencies ($\Delta f = 10$ kHz) and opposite propagation direction were excited by the IDTs. The signal from the rf generators was electrically mixed down to the difference frequency and fed into a lock-in amplifier as reference for analyzing the signal picked up via the LFM detection. No significant signal was found in the standard AFM detection used by conventional SAFM. Figure 3 shows the spatially resolved phase difference between the reference and LFM-detected signal. The occurrence of this signal is a strong indication of the nonlinearity in the lateral force interaction. In analogy to SAFM mixing, the detected signal corresponds to an additional torque with a phase determined by the difference between the phase arguments of the superimposed waves. This phase consists of a temporal term and a term linearly increasing with propagation distance. The spatial derivative of the latter one is given by the difference of both **k** vectors. The sawtoothlike behavior of the phase image is due to the measurement range of the lock-in amplifier between $-180°$ and $180°$. The phase jumps occur with a periodicity of $\lambda_{SAW}/2$, reflecting the phase delay of the two acoustic waves propagating in opposite directions.[9] On the fused silica surface, a phase velocity $v_{exp} = 4868$ m/s was measured at the frequency $f = 340.914$ MHz, which deviates from theoretical calculations ($v_{th} = 4947$ m/s) by less than 2%. On the Au layer, the SAW wavelength was measured at the center frequency of the passband $f = 339.785$ MHz, ($\lambda_{SAW} = 13.39$ μm) and two frequencies within the first sidebands $f = 338.252$ and 340.909 MHz (corresponding to $\lambda_{SAW} = 13.44$ and 13.31 μm, respectively). The phase velocities determined for this layered structure were $v_{exp} = 4546$, 4550, and 4537 m/s. They differ from the calculated values by about 5%. Similar phase velocity measurements were carried out for STWs at frequencies up to 960 MHz.[10]

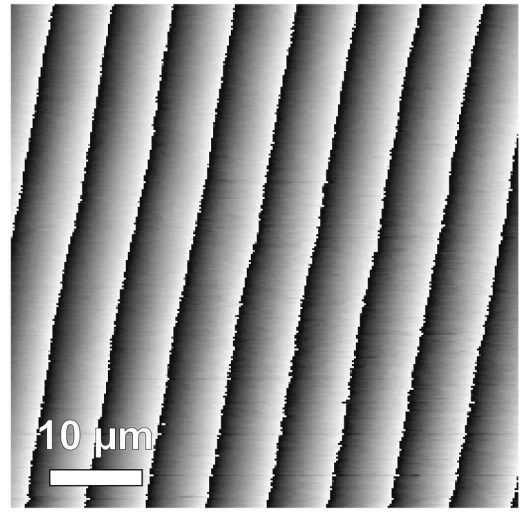

FIG. 3. LFM-SAFM measurement of the mixing of two Love waves. The 360° phase jumps occur with a periodicity of 6.65 μm corresponding to the half wavelength of the incident waves.

The nonlinearity of the tip-to-sample interaction that enables the mixing of the transversely polarized acoustic waves can also be exploited in the sense of a mechanical diode reflecting the nonlinearity in its rectifying properties. This has been used for the investigation of standing acoustic wave fields. Launching two propagating Love waves from the opposing IDTs establishes a standing wave field with a periodicity of $\lambda_{SAW}/2$. By modulating the rf signal's amplitude at some kHz and analyzing the LFM signal by a lock-in amplifier the lateral amplitude distribution of the standing wave field is mapped. Figure 4(b) shows the acoustic field on the

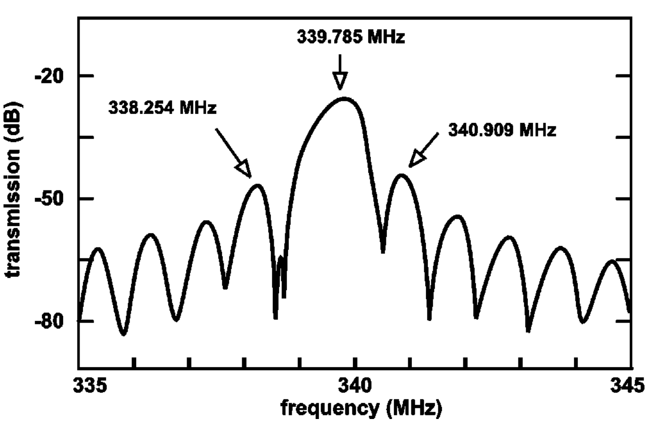

FIG. 2. Amplitude passband characteristic for the Love wave device Au/SiO_2/quartz. The center frequency was 339.785 MHz and the bandwidth about 1 MHz. Two sidelobes at 338.254 MHz and 340.909 MHz have also been investigated.

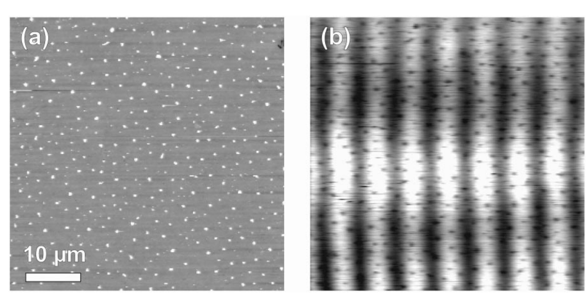

FIG. 4. Topography (a) and LFM-SAFM amplitude image (b) of a standing wave field on the system Au/SiO_2/quartz.

Au layer in the wave's propagation path between the IDTs. The amplitude maxima (bright bars) exhibit a periodicity of 6.5 μm, corresponding to a wavelength of 13 μm. A brightness modulation along the acoustic wave fronts can be seen as well as a slight distortion of the wave-front shape. This is due to diffraction or scattering effects caused by surface inhomogeneities outside the imaged area. The dark dots correspond with grainlike imperfections of the Au surface. They appear as bright spots in the topography image in Fig. 4(a). At these spots, the elastic coupling between tip and surface is changed, leading to a decrease in the measured wave amplitude. The phase image, however, is not influenced by those surface inhomogeneities, thus allowing the separation between phase information of the wave field and topographical features.

In this letter, we present a method for the investigation of acoustic wave phenomena on the surface of a solid, based on scanning acoustic force microscopy operated in lateral force mode. By analyzing the torsion of the cantilever in addition to its bending, in-plane and vertical oscillation components due to acoustic waves can be measured. The key for the detection is in both cases the nonlinear characteristic of the tip-to-sample interaction. This is proven by the fact that acoustic mixing of two Love waves was observed at this interaction, delivering the phase change of the acoustic wave field. By that, its phase velocity can be obtained, which is in good agreement with numerical calculations.

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